New-Fangled Approach to Predict the Behaviour of Composite Sandwich Pavements

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***Abstract* - The significance of this research lies in the reduction of cost of construction of roads by arriving at an economically feasible pavement. This is accomplished by studying the response of thick composite sandwich plate, supported continuously, for the cyclic loading condition at various stress ratios and is compared with plain slabs placed on similar support condition. A conceptual pavement model was examined using lean cement concrete as the sandwiched material. The behaviour of the plain and composite slabs was then studied experimentally by static and dynamic tests. The constraints in the course of testing were the number of cycles of failure and the crack length. The results obtained prove that the use of composite rigid pavement slab for pavement construction is convenient and economically feasible as 50% of the cement content gets reduced, which indeed results in the reduction of the cost of construction for approximately 20% - 30%. The composite sandwich pavements thus serve as a long-lasting and an effective alternate for roadways carrying very heavy traffic.**

***Index words* - composite structures, sandwich plates, thick plates, composite rigid pavement slab, sandwich concrete pavements**

I. Introduction

Road transportation plays a vital role in the economic development of a country in today's scenario. The surface of the road should be stable, non-yielding and should permit heavy load traffic. The other main concern is the ability of the road surface for the fast vehicles to move safely and comfortably at the design speed. Construction of road networks to meet the demand in transport consumes key part of the country's wealth. Hence this vital transport need has to be made cost-effective without any failure in structure and strength of the pavements.

Compared to flexible pavements, a rigid pavement proves to be advantageous due to the following reasons:

(i) It possess sufficient flexural strength to transmit the wheel load stresses to a wider area below
(ii) The load is distributed by the slab action
(iii) It behaves like an elastic plate resting on a viscous medium.

Due to these reasons rigid pavements are preferable. In the analysis of structural elements resting on a continuous medium such as concrete pavements of roads, the problem is usually simplified and analyzed as an idealized rectangular plate with four edges supported by an elastic foundation.

In the rigid pavements though the thickness of the pavement is same the stress diagram varies. Stresses are greater at top and bottom while it gradually tapers towards the centre. In this way the material used in the region of neutral axis can be replaced consequently with a secondary material in order to minimize the cost.

II. General Behaviour Of Composite Pavement

A. Composite Sandwich Pavement

The composite rigid pavement is that which has heterogeneous layers. A sandwich pavement is a composite pavement consisting of a rigid overlay placed on top and bottom of a semi-rigid layer. The non-rigid layer may be bituminous concrete for its full depth or a combination of bituminous concrete and granular base course. When the thickness of the nonrigid layer is less than 102 millimetres, the entire pavement will be treated as a rigid overlay on rigid pavement and the nonrigid material will be considered to be a bond-breaking course. The secondary materials which can be used in composite slab are of different kinds like bricks, jute, fibres and Lean Cement Concrete (LCC).

B. Uniqueness of composite slabs

1) Loading: Composite slabs consisting of cold-formed light-gauge steel sheets and normal or lightweight concrete have been used extensively under static loading conditions but are generally not used under heavy moving loads. Preliminary tests indicated a favourable response when these composite slabs were subjected to repeated loadings.

A detailed composite slab design by nature is a two step process. Under constructional cycles, the profiled steel sheeting behaves as a thin walled steel plate structure while under live load it is already a composite system with the concrete set on it.

2) Transverse Shear: Shear normally occurs between the plates which lead to the failure of composites. It may also happen that under repeated loading, though the first slip occurs, it continues to take up the load till all the layers develop crack.

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Fatigue Behaviour: The fatigue behaviour of plain concrete subjected to relatively slow loading-unloading cycles indicate that the specimens submitted to uniaxial cycles experienced an increase in static strength in comparison with the reference ones. The distribution of fatigue life of concrete under a given stress level was found to approximately follow the Weibull probability law [5].

4) *Cracking:* Cracking of concrete in composite slabs has a major influence on the distribution of horizontal shear forces between the sheeting and concrete. Hence it has impact on the behaviour of the composite slab.

III. Hypothesis

H.M.Westergaard is considered the pioneer in providing the rational treatment of the rigid pavement analysis. He proposed that pavements are homogeneous, incompressible and permit only downward displacement as a whole without any lateral displacement. But the drawback was the transverse shear deformation and local effects were not taken into account. This was then modified by Reissner and Mindlin for the thin plate theory, which inferred that for the plate structures supported by elastic foundation the transverse shear deformation, the local effects in the plates and the transverse connection in the foundation must be considered [1], [7].

The behaviour of sandwich plates were highly non-linear as compared to that of homogenous plates and the inclusion of terms relating to full non-linearity in the formulation affected the frequencies of thick plates [2]. Stress recovery in the laminated composite and sandwich panels undergoing finite rotation showed that they are susceptible to mechanical damages in the transverse direction due to their relatively low strength in the transverse direction [3].

The deflection of sandwich plate can be composed of two components: bending and shear deflections. The partial deflections can be determined by a method called 'two-step expansion'. The fundamental equation and general solution may be obtained by considering the governing differential equations for the bending and shear deflections [4].

IV. Enhanced Incremental Approach

A. *Thick Plate Analysis*

In the present analysis a thick plate is assumed since the thickness to span ratio is greater than 5%. Based on Mindlin's theory thin plate analysis should be done if ratio of thickness of the plate to that of the span is less than 5% else the thick plate analysis should be done.

The reason behind thick plate analysis was:

Proposed plate is of dimension = 300 x 300 x 60 mm

Thickness / span = 60 / 300 = 0.2

0.2 is greater than 0.05 (5%)

Hence the thick plate analysis was executed.

To study the response of the thick composite plate an idealized rectangular plate is considered with all the four edges continuously supported which provides an elastic foundation.

B. *Concept of Economical Feasibility*

The material used in rigid pavement is homogeneous throughout the entire structure. But the stress diagram of a rigid pavement seems to be varying considerably. It is observed that the stress is greater at top and bottom of the pavement and gradually reduces towards the centre and becomes zero at the neutral axis of the pavement. Consequently, the concrete present around the area of neutral axis seems to be wasted. In this way the material used in the region of the neutral axis to the thickness of h/4 can be replaced accordingly with a secondary material, where the bending stress is minimum (about 2MPa). Hence, the rigid slab with heterogeneous material acts as a composite thick plate.

C. *Theoretical Model of Composite Slab*

Fig. 1. shows the model of the composite slab used in the present study (the colour differentiations between layers are shown for clarity). It is a measure of 60 cm, in which a height of h/4 was replaced by the low cost material lean cement concrete. The layers of a composite rigid pavement thus consists of a rigid overlay (PQC- Pavement Quality Concrete) placed on top and bottom of a semi-rigid layer (LCC – Lean Cement Concrete).

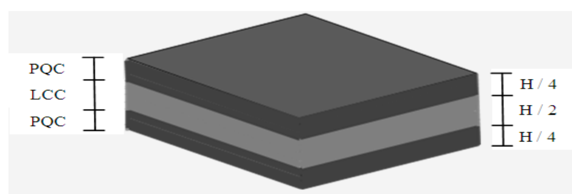

Figure 1. Conceptual model of composite slab

D. *Stress Distribution in the Composite Slab*

Fig. 2. indicates the stress pattern of composite slab at different layers. Stresses in extreme fibres of the composite slab are maximum which is 5 MPa, and is then reduces constantly to zero at neutral axis.

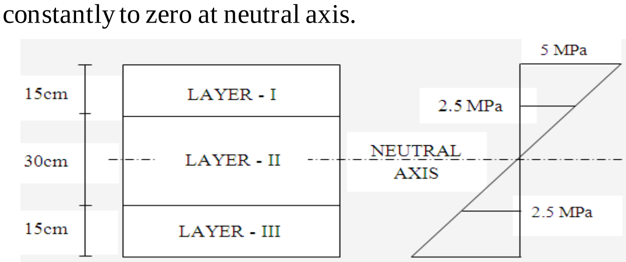

Figure 2. Combined stress diagram

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In plain slabs, pavement quality concrete was used throughout the entire thickness. But in composite slab, middle layer was replaced with lean cement concrete of comparatively of low strength whereas the top and bottom layers were laid with pavement quality concrete of high strength.

E. Arriving Mix Proportions for plain and composite slab

1) Materials: The materials such as cement, aggregates and water were used in the present work. Cement used was 53 grade ordinary Portland cement and the water cement ratio used here was 0.52 was kept constant. The characteristics of fine and coarse aggregates such as grading of fine and coarse aggregates, proportioning of aggregates by Rothfutch's method and maximum density test, direct shear test and sieve analysis for the sand bed were studied using procedures described by IS 2386 (part II & III) 1968.

2) Mix Proportioning: The dimensions were proposed based on the available testing facility. Initially, reference mixes were done by means of three mix proportions of different cement content and constant water-cement ratio. Mix proportioning was carried out for PQC and LCC separately. 6 cubes and 3 beams were casted and were kept for curing, for each mix design separately. Mix Proportioning which was carried out is tabulated in Table I.

TABLE I.
MIX PROPORTIONING

Mix	Water	Cement	Fine Aggregate	Coarse Aggregate
	(litre/m3)	(kg/m3)	(kg/m3)	(kg/m3)
Reference mix	214.2	412	599.97	1088.42
Trial mix I	104	200	769.928	1397.97
Trial mix II	130	250	729.45	1325.03
Trial mix III	156	300	689.293	1251.36

3) Mix design parameter for Pavement Quality Concrete(PQC): The design parameters for PQC is as follows:

(i) Modulus of rupture (MOR) should be minimum of 4 MPa.

(ii) Compressive strength should be minimum of 35 MPa.

4) Mix design parameter for Lean Cement Concrete (LCC): For the desired MOR value which is of 2 MPa, the minimum cement content is to be obtained. Cubes were tested in compressive strength testing machine and beams were tested in CBR apparatus for flexure.

Fig.3. indicates the graph plotted between the cement content and Modulus of rupture. Thus for 2.5MPa compressive strength, the cement content was obtained as 280kg/m3.

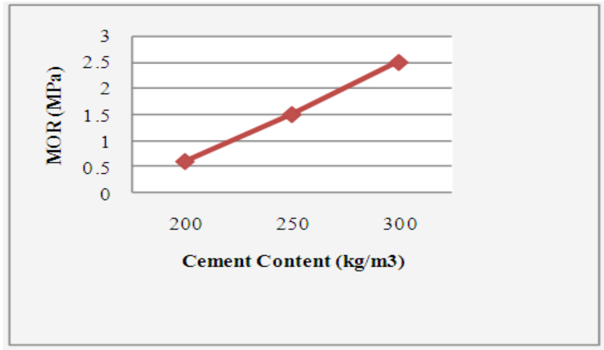

Figure 3. Compressive strength results

Thus for the desired MOR value, corresponding cement content was obtained, which paved the way for the selection of mix proportions of plain and composite slabs.

F. Methodology

1) Dimensioning: The total number of slabs casted was 42. Among which 21 were plain slabs and 21 were composite slabs with a dimension of 300 x 300 x 60 mm each. The layer thickness of composite slab casted is as shown in Fig.2.

2) Casting: The cement content used for plain slab was 300kg/m^3 throughout the entire thickness. For the composite slab, two concrete mixes were prepared. The bottom layer was first laid with the cement content of 300kg/m for 15cm.The next layer was laid of cement content 200kg/m for 30cm and the remaining layer of 15cm was laid with 300kg/mmix. The casted and cured slabs were mounted on sand bed which served as continuous support.

3) Testing: In each category, 3 specimens were tested in Universal Testing Machine for static test and the ultimate load was obtained which is explained in Table II. From the static test results, average ultimate load were found. Dynamic tests were done in universal fatigue machine applying average ultimate load with different stress ratios. The stress ratios taken were 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8. Three slabs for each stress ratio were tested and the results were tabulated.

The parameters considered for the comparison of plain and composite slabs were number of cycles of failure, deflection and crack length. While testing, deflection of the slab was found to be negligible hence it was not considered. Thus number of cycles of failure and crack length was taken as parameters.

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TABLE II.
DETAILS OF TESTING

Tests	Number of specimens		Support condition	Experimental Set up
	Plain	Composite		
Static test	3	3	continuous	Universal Testing Machine
Dynamic test	18	18	continuous	Universal Fatigue Testing Machine

V. RESULTS AND ANALYSIS

A. Test Results

1) Static test results for Plain and Composite slabs: The plain slabs and composite slabs were tested in universal testing machine and the respective ultimate loads observed during testing are tabulated in Table III.

TABLE III.
STATIC TEST RESULTS FOR PLAIN AND COMPOSITE SLABS

Samples	Ultimate load (kg) for plain slabs	Ultimate load (kg) for composite slabs
1	1540	1110
2	1590	2000
3	2110	1700

Consequently the average ultimate load obtained by static test was 1476kg for plain slabs and 1570kg for composite slabs. This ultimate load with six different stress ratios was considered for the dynamic test.

2) Dynamic test results for Plain and Composite slabs: The plain slabs and composite slabs were tested in fatigue testing machine and the respective values are tabulated in Table IV.

B. Discussion

In plain slab, flexure alone acts at the ends of the slab but in composite slab both flexure and shear resistance between the layers plays the role for the failure of the slab. In this analysis, the failure of composite slab for stress ratio below 0.6 was not possible as the shear resistance also comes into act. But in plain slabs the lack of shear resistance made the slab to fail at lower stress ratios. Fig.4. shows the failure pattern of composite and plain slab.

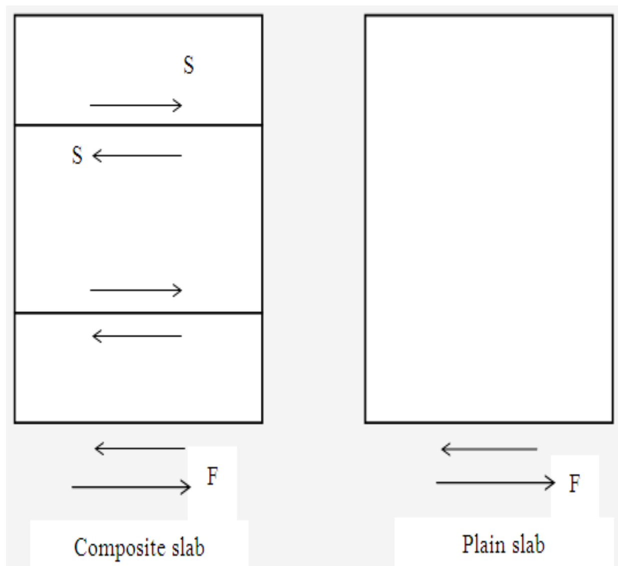

Figure 4. Comparison of composite and plain slabs at failure

TABLE IV.
DYNAMIC TEST RESULTS FOR PLAIN AND COMPOSITE SLAB

Stress Ratio	Plain slabs		Composite slabs	
	Average number of cycles at failure	Average crack length	Average number of cycles at failure	Average crack length
0.3	144	36.67	>20,000	-
0.4	120	51.50	-	-
0.5	23	52.00	-	-
0.6	20	52.67	>20,000	-
0.7	17	52.67	25	32.00
0.8	10	66.30	20	57.00
0.85	-	-	20	44.00
0.875	-	-	18	43.00
0.9	-	-	10	48.00
1.0	-	-	10	31.00

The observations monitored during the Dynamic test analysis are as follows:

1) Shaft Movement: When load was applied, the sand bed which was considered as continuous support got densified first. Only after the sand bed reached its refusal densification stage, the slab started to take the load. Refusaldensification is that the stage where the sand restricts densification further. But the position when the slab actually took the load was not observed since it was not exactly visualized. For lower stress ratio, lower would be the shaft displacements and vice-versa.

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2) Load Failure: As the slab was continuously supported, the failure was due to compression and not due to flexure. Until the sand bed getting compressed completely, the slab found to rebound due to the transfer of load to sand bed. After the sand bed getting densified, the slab underwent compression and failed at the yield point. No failure was caused up to 0.6 stress ratio.

3) Upheaval: As soon as the load is applied to the slab, the sand exactly underneath the slab would be densified and standstill. But the sand at the edges being loose got displaced from its position. The displacement of sand from its position is said to be the upheaval. Due to upheaval of sand the deflection of the slab differed from its original deflection, which was simply supported.

4) Crack length: When the slab getting failed, crack appeared on the surface. The pattern in which the crack appeared was studied for each slab and the crack length for each slab was tabulated as shown in TABLE IV. The crack pattern for both plain and composite slabs resembled the same. Hence, from the present analysis the composite sandwich slab was found to be an effective alternate for plain slab which is practical and economically feasible.

VI.CONCLUSION

In this research work, extensive study was made on composite rigid pavement slab and its behaviour. The failure load for both plain and composite slabs were compared based on average number of cycles at failure, which was found to be equal from the 0.6 stress ratio. The failure pattern between the layers was homogenous. No de-bonding was found between the layers of the composite slab as the bond strength between the layers of concrete in composite slab was excellent. Crack pattern was observed to be the same for both the types of the slabs, plain and composite, at failure for different stress ratios. For the same thickness of composite slab and plain slab the flexural strength seemed to be varied from 2% – 10%.

Thus the use of composite rigid pavement slab for pavement construction is practical and economically feasible as 50% of the cement content gets reduced, which indeed results in the reduction of the cost of construction.

VII.FUTURE ENHANCEMENTS

This research can be enhanced further by other materials such as brick powder, fly ash and fibre as secondary material in spite of lean cement concrete (LCC). Also, in the present analysis the support conditions used was only continuous support which can also be tested under different support conditions like Corners support and Edge support.Load applied was concentrated loading, which was the extreme loading condition. It can be tested for different loading conditions like axial loading. The support condition was continuous throughout the slab and sand bed was compacted to its maximum density. It can also be replaced by using different types of soil conditions.Thus in future this analysis can be extended to achieve the maximum reduction in cost of construction of roads which will in turn be a great boon to a country's economy.

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